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Introduction
The introduction of the klapskate in speed skating has resulted in a remarkably improvement in speed skating performances. In contrast to the conventional type of skates, klapskates incorporate a hinge between shoe and blade that allows the foot to rotate independently of the skate blade. It has been suggested that the increased performance with klapskates compared to conventional skates could be attributed to the difference in the position of the center of rotation of the foot relative to the ice (Houdijk et al. 2000, 2001). With both skates skaters plantar flex the ankle to the same extent at the end of the push off. However, with conventional skates, plantar flexion occurs while the foot rotates around the front end of the long skate blade; while with klapskates the foot rotates around the hinge of the skate underneath the ball of the foot. The long effective length of the foot segment, which is imposed by the conventional skate, seems to obstruct the generation of work per stroke. Based on this conclusion, it can be hypothesized that the position of the hinge is an important factor in klapskate design. It is presently, however, unknown how klapskate hinge position affects the dynamics of the push off and the work output during a stroke in speed skating. In the current study a computer simulation model of the push off in speed skating was used to investigate the relation between klapskate hinge position and the generation of work per stroke in speed skating.

Methods
A model of the musculo-skeletal system was designed that simulated a simplified, 2-dimensional skating push off (Bobbert et al. 2001). In fact, the model performed a one-leg vertical jump on a frictionless surface. A penalty was set on trunk rotation in order to mimic the body position of speed skating. The model consisted of three rigid segments representing the foot, lower leg, upper leg and one lumped rigid segment combining the trunk, head, arms and swing leg. The distal end of the foot segment represented the hinge of the klapskate. Therefore, the length of the foot segment determines hinge position. In current klapskates the hinge is located approximately 170 mm anterior to the ankle joint. The tip of the blade of the conventional skates is located approximately 280 mm anterior to the ankle joint. Therefore, the length of the foot segment of the model was systematically changed such that the hinge position (the horizontal distance between ankle joint and distal end of the foot segment) was varied between 30 mm and 280 mm. The segments were actuated by six Hill-type leg muscles: m. gluteus, hamstrings, mm. vasti, m. rectus femoris, m. soleus and m. gastrocnemius. Initial muscle activation was set to maintain static equilibrium. Subsequently muscle stimulation was allowed to switch to half of full activation once. Half of full

Figure 1: Total Work generated by the muscles ($W_{\text{mus}}$) and the part of the muscle work that effectively contributes to the propulsion of the body’s center of mass ($W_{\text{eff}}$) versus klapskate hinge position. The dimension of a regular klapskate is plotted in the background for reference.
activation was chosen instead of full activation to account for the fact that the speed-skating push off is a repetitive motor task. Therefore, each individual push off is submaximal depending on the distance that has to be skated. The onset times of stimulation of the six leg muscles were optimized to obtain maximal work per stroke (i.e. jump height) for each hinge position. A penalty was included in the optimization criterion to restrain trunk rotation.

**Results**

Maximal work per stroke was obtained with the hinge positioned at 150 mm and decreased by approximately 25% at either extreme (Fig. 1). Changing hinge position with respect to this optimum predominantly affected the generation of muscle work ($W_{mus}$). However, it also affected the fraction of muscle work that was converted into effective work ($W_{eff}$; the work contributing to the vertical propulsion of the body’s center of mass).

Hinge position appeared to primarily affect the timing of the onset of foot rotation. Rotation of the foot occurs when the net joint moment around the ankle, which is generated by the plantar flexor muscles, exceeds the couple of reaction forces that act on the foot (Fig. 2). Balance between the net ankle moment and the couple of reaction forces can be maintained as long as the center of pressure of the ground reaction force can shift forward, which increases the moment arm ($r$) of the couple. The position of the hinge of the skate determines the maximal moment arm of the couple of reaction forces and hence determines when the foot will start to rotate in response to a given net ankle moment and reaction forces.

![Figure 2: (above) A freebody diagram of the foot. Initially the net ankle moment ($M_A$) is in equilibrium with the couple of external force (i.e., the net joint reaction force ($F_A$) and ground reaction force ($F_{grf}$)). The mass of the foot is ignored. The moment arm ($r$) of the couple reaches its maximal value when the center of pressure of the $F_{grf}$ reaches the hinge. Thereafter an increase in $M_A$ or decrease in reaction forces will result in a rotation of the foot.](image1)

![Figure 3: (right) Time histories of $F_{grf}$, $M_A$ and the foot angle ($\phi_f$) for a push off with the hinge at the optimum position (150 mm, solid), posterior to the optimum (120 mm, dashed) and anterior to the optimum (170 mm, dotted). Take off occurred at $t=0$ s.](image2)
When the hinge position in the model was placed anterior to the optimal position, the maximal moment arm of the couple of reaction forces exceeded a critical length. Beyond this length the maximal ankle moment that could be generated by the plantar flexor muscles was not sufficient to initiate an early rotation of the foot. Foot rotation was inevitably delayed until the hip and knee joint moments decreased and the reaction forces dropped (Fig. 3). This delay in foot rotation affected the dynamics of the entire leg system. The Most importantly it resulted in an increase of all joint angular velocities and, consequently, muscle shortening velocities. This reduced the ability of the muscles to develop force and hence generate work. Due to the dys-synchronisation of the leg segment rotations, the increased joint angular velocities did not result in an increased velocity of the BCM. Instead the high angular velocities reduced the effective work, since work flowing to rotational kinetic energy of the leg segments increased.

When the hinge was placed posterior to the optimal position, foot rotation could be initiated more easily. The shorter the maximal moment arm of the couple of reaction forces, the less the plantar flexor moment has to be built up to initiate foot rotation. When the hinge was placed posterior to the optimum position the activation of the plantar muscles was delayed compared to the push off with optimal hinge position. This prevented a premature rotation of the foot, which would otherwise have resulted in a premature take off with incomplete extension of the knee and hip joint. However, the delay in the activation of the plantar flexors also reduced their active state during the first part of their range of shortening and, hence, their work output.

Discussion and conclusion
The simulation experiment performed in this study revealed that push-off performance of our model critically depends on klapskate hinge position. The position of the hinge was shown to affect the timing of rotation of the foot segment. This affected a balanced sequence of the individual leg segment rotations. A balanced sequence of segmental rotations is required to ensure a high work output of all leg muscles. As can be seen, it prevents a premature take off, so that muscle can produce work over a full range of shortening. It also prevents that muscle shortening velocities become unnecessarily high. The hinge position that results in a maximal work output, is therefore that position that allows a timely onset of foot rotation, without requiring a reduction in the activation of the plantar flexor muscles. Obviously this hinge position depends on the properties of the entire musculo-skeletal system of the skater, including morphology, geometry and muscle properties.

Despite the simplicity of the model, the results appear to be consistent with previous observations made in speed skating experiments. The effect of hinge position on the timing of foot rotation and joint angular velocity were demonstrated previously (Houdijk et al. 2001, Allinger and Motl 2000). These observations could, however, not be related to push off performance since no significant effect on work output was found in these experiments. The optimal hinge position predicted by our model does, however, not comply with current trends in speed skating. Elite skaters tend to place the hinge more to anterior compared to our simulation model. So, despite the fact that the simulation model helps to clarify the effect of hinge position on the generation of work per stroke, it proves to be too simple to make reliable predictions of the optimal klapskate hinge position for speed skating.

References

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